Cardiovascular fitness and thermoregulation during prolonged exercise in man

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Summary

Nine healthy male subjects differing in their training status (VO₂ max 54±7 ml.min⁻¹.kg⁻¹, mean±SD; 43-64 ml.min⁻¹ kg⁻¹, range) exercised on two occasions separated by one week. On each occasion, having fasted overnight, subjects exercised for 1 h on an electrically braked cycle ergometer at a workload equivalent to 70 per cent VO₂ max (test A) or at a fixed workload of 140 W (test B). Each test was assigned in a randomized manner and was performed at an ambient temperature of 22.5±0.0°C and a relative humidity of 85±0 per cent. Absolute exercise workload was the most successful predictor of sweat loss during test A (r=0.82, p<0.01). Sweat loss was also related to VO₂ max tests A (r=0.67, p<0.05) and B (r=0.67, p<0.05). There was no relationship between resting pre-exercise core temperature and VO₂ max. However, core temperature recorded during the final min of exercise in test B was inversely related to VO₂ max (r=−0.86, p<0.01). As a consequence, core temperature during the final minute of exercise was also related to the relative exercise intensity (%VO₂ max) performed (r=0.82, p<0.01). The heart rate response during test B was inversely related to VO₂ max (r=−0.71, p<0.05) and was positively related to the relative exercise intensity performed (r=0.68, p<0.05). No relationship was found between mean skin temperature during the final minute of exercise and the relative (r=0.26) or absolute (r=0.03) workloads performed during exercise. The results of the present experiment suggest that cardiovascular fitness (as indicated by VO₂ max) will have a significant influence upon the thermoregulatory responses of Man during exercise.

Keywords: Thermoregulation, sweat loss, VO₂ max, exercise

Introduction

It has been generally accepted that physical training will to some extent precondition Man to exercise in the heat by improving heat dissipating function (heat acclimatization). Piwonka et al. indicated that the strenuous daily exercise performed by competitive distance runners will result in total heat acclimatization and may be used as an effective method of preconditioning men to work in the heat. Strydom and Williams demonstrated that a less severe training programme will improve heat tolerance, but will not completely acclimatize individuals to work in the heat. Several authors have suggested that the condition of heat acclimatization seen in highly trained individuals may possibly be the result of the repeated hyperthermia experienced by such individuals during their daily training session. Furthermore, Henane et al. postulated that repeated exercise-induced hyperthermia will result in trained individuals becoming more responsive to core temperature changes (heat adaption). However, it has also been proposed that improvements in heat dissipating function may be the direct result of an exercise-induced alteration in cardiovascular function thereby allowing a greater volume of blood to perfuse the skin of the trained individual at any fixed submaximal workload.

Few studies have attempted to differentiate between the separate influences of heat acclimatization and cardiovascular adaptation on heat dissipation during exercise. Schwartz et al. concluded that improvements in heat dissipating function arising from a period of physical training in the heat are largely the result of heat adaptation. However, because the intensity of daily training performed by subjects in that study was very low (41 W), the contribution made by an improvement in cardiovascular function to heat dissipation was not adequately assessed.

The present experiment was therefore undertaken to re-examine the proposal of Schwartz et al. that heat adaptation will be the dominant factor influencing Man’s thermoregulatory responses during exercise at moderate temperatures.

Methods

Nine healthy male volunteers were pre-selected to take part in the experiment on the basis of their training status and aerobic capacity (VO₂ max). Subjects ranged from untrained but recreationally active (VO₂ max 40–45 ml.min⁻¹.kg⁻¹) to well trained (VO₂ max 60–65 ml.min⁻¹.kg⁻¹). However, none of the subjects was highly trained (VO₂ max >65 ml.min⁻¹.kg⁻¹, Table 1).
Thermoregulation during exercise: P.L. Greenhaff

The experiment was undertaken within an environmentally controlled climatic chamber between the months of February and March.

Prior to commencing the experiment, VO₂ max was measured in all subjects during a discontinuous stepwise test with the use of a semi-automated on-line gas analysis system (Gould 9000 IV Computerized Pulmonary Exercise Lab, Cardiokinetics, Salford, UK). Each VO₂ max test and all subsequent exercise tests were performed on an electrically-braked cycle ergometer (Siemens EM 840, Siemens Ltd., Sunbury-on-Thames, UK). At least four days after the determination of VO₂ max subjects performed a 1h ‘trial test’ at a workload calculated to be equivalent to 70 per cent VO₂ max. The purpose of this test was to confirm that pre-determined workload was equal to 70 per cent VO₂ max and also to ensure that the exercise intensity could be sustained for a 1h period.

Following a one week ‘recovery period’ subjects reported to the laboratory on two further occasions, separated by one week. On each occasion, having fasted overnight, subjects either exercised for 1h at a workload equal to 70 per cent VO₂ max (test A) or for 1h at a fixed workload of 140 W (test B). Each test was assigned in a randomized manner. The experimental protocol was designed with the prior knowledge that the sweating response of Man during exercise is closely related to the absolute workload performed, while the core and skin temperature responses are more related to the relative workload performed. Each test was assigned in a randomized manner and was performed at an ambient temperature of 22±0.5°C and relative humidity of 85±0 per cent.

Prior to both tests nude body weight was recorded, a rectal temperature probe (Clandon Southern, Aldershot, UK) was inserted to a depth of 14 cm beyond the external anal sphincter, and a three lead ECG (Consolidated Medical Equipment, New York, USA) and four temperature probes (Comark Electronics, Rustington, UK) were fixed to the skin. Skin temperature was measured at the four sites of mid-dorsal upper arm, lateral chest, mid-thigh and mid-calf with the use of a digital microprocessor thermometer (Comark Electronics, Rustington, UK) and the values obtained were used to calculate weighted mean skin temperature according to the method described by Mitchell and Wyndham.

For the 10 min immediately prior to each exercise test, subjects sat at rest on the cycle ergometer. During this time period and the following exercise test, recordings of relative humidity, heart rate and skin, rectal and room temperature were made every 5 min. Heart rate was measured using a medical heart rate monitor (Kontron Instruments Ltd., St Albans, UK), relative humidity using a hair hygrometer (Gallenkamp, Loughborough, UK) and room and rectal temperature using a YSI Tele thermometer (Clandon Southern, Aldershot, UK). In addition, a 2 min gas sample was collected every 15 min during each exercise test using the Douglas bag method. Each expired gas sample was used to determine carbon dioxide (Beckman LB-2 CO₂ analyser, Beckman–RJIC Ltd., High Wycombe, UK) and oxygen (Servomex O₂ analyser, Servomex Ltd., Crowborough, UK) content, gas volume (Harvard digital dry gas meter, Harvard Apparatus Ltd., Edenbridge, UK) and gas temperature (Comark digital microprocessor thermometer, Comark Electronics, Rustington, UK). The values obtained were used to calculate oxygen consumption during exercise.

Upon completion of the exercise task, skin and rectal temperature probes were removed. Subjects then showered and after the removal of surface water, nude body weight was again recorded. Water lost as sweat was estimated after correction for respiratory weight loss.

Statistical analysis involved the use of bivariate linear regression and the determination of the Pearson correlation coefficient (Minitab statistical package, Pennsylvania State University, USA). Values shown in the text are presented as mean±SD; in the figures as mean±SE. On occasion, in an effort to demonstrate the population distribution mean, SD and range are presented in the text.

This study was approved by the local Ethics Committee.

Results

Physical characteristics

The physical characteristics of subjects involved in the present experiment are shown in Table 1. Maximal oxygen uptake (VO₂ max) covered a wide range (43–64 ml.min⁻¹.kg⁻¹) and was not related to body height (r=0.46), body weight (r=0.60), body surface area (r=0.63) or age (r=−0.43). In test A, subjects exercised at a workload of 193±34 W (mean±SD; range 140–235 W). This was equivalent to 70±4 per cent VO₂ max (range 66–75 per cent VO₂ max). In test B, workload was fixed at 140 W. In relative terms this was equal to 50±13 per cent VO₂ max (range 35–68 per cent VO₂ max). The absolute workload performed in test A was related to body weight (r=0.78, p<0.05), body surface area (r=0.83, p<0.01) and VO₂ max (r=0.94, p<0.001). In test B, as expected, the relative exercise intensity at which exercise was performed (per cent VO₂ max) was inversely related to body weight (r=−0.68, p<0.05), body surface area (r=−0.72, p<0.05) and VO₂ max (r=−0.95, p<0.001).

Sweating responses

Sweat loss in test A (932±383 g; range 341–1410 g) was equal to 1.3±0.5 per cent of pre-exercise body weight and was related to body weight (r=0.82, p<0.01).

Table 1. Physical characteristics of subjects (n=9)

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Surface Area (m²)</th>
<th>VO₂ max (ml.min⁻¹.kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>28</td>
<td>178</td>
<td>68.5</td>
<td>1.84</td>
</tr>
<tr>
<td>SD</td>
<td>6</td>
<td>178</td>
<td>5.8</td>
<td>0.08</td>
</tr>
<tr>
<td>Range</td>
<td>20–40</td>
<td>174–182</td>
<td>60.7–78.9</td>
<td>1.75–1.97</td>
</tr>
</tbody>
</table>

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Figure 1. Relationship between absolute workload performed and absolute sweat loss during test A. Measurements were made on 9 male subjects who exercised for 1 h on an electrically braked cycle ergometer at 70 per cent VO2 max.

Figure 2. Relationship between maximal oxygen uptake (VO2 max) and absolute sweat loss during test A (●) and test B (○). Measurements were made on 9 male subjects who exercised for 1 h on an electrically braked cycle ergometer at 70 per cent VO2 max (test A) and 140 W (test B).

body surface area \( r = 0.85, p < 0.01 \), absolute exercise workload \( r = 0.82, p < 0.01 \) Figure 1 and VO2 max \( r = 0.67, p < 0.05 \) Figure 2. Sweat loss in test b \( (468 ± 123 \text{ g}; \text{range} 349–702 \text{ g}) \) was equal to 0.7±0.1 per cent of pre-exercise body weight and was related only to VO2 max \( r = 0.67, p < 0.05 \) Figure 2.

Rectal temperature responses

Rectal temperature increased gradually throughout exercise in test B (Figure 3), rising from 37.0±0.4°C immediately prior to exercise to 38.2±0.3°C during the final min of exercise. During test A there was no increase in rectal temperature until after 5 min of exercise when values were seen to increase from 37.1±0.2°C to 39.0±0.5°C recorded during the final min of exercise. As expected, the rise in rectal temperature during test A was more marked than the rise recorded in test B. In tests A and B resting pre-exercise rectal temperature was not related to VO2 max \( r = 0.01, r = -0.10 \) respectively.

However, rectal temperature during the final minute of exercise in test B was inversely related to VO2 max \( r = -0.86, p < 0.01 \) Figure 4) and was positively related to the relative exercise intensity (per centVO2 max) at which exercise was performed \( r = 0.82, p < 0.01 \) Figure 4). This was not the case in Test A \( r = 0.43, r = -0.46 \) respectively; rectal temperature recorded during the final minute of exercise was related only to resting pre-exercise heart rate \( r = 0.72, p < 0.05 \). Rectal temperature recorded during the final minute of exercise in test B was not related to pre-exercise heart rate \( r = 0.27 \) but was related to heart rate recorded at the same point \( r = 0.71, p < 0.05 \) Figure 5A). In addition, the change in rectal temperature during exercise in test B was related...
Thermoregulation during exercise: P.L. Greenhaff

![Graph showing relationships between maximal oxygen uptake (VO_2 max) and 60 min exercise core temperature (O) and relative exercise workload (per cent VO_2 max) and 60 min exercise core temperature (△). Measurements were made on 9 male subjects who exercised for 1 h on an electrically braked cycle ergometer at 140 W (test B).](image)

Figure 4. Relationships between maximal oxygen uptake (VO_2 max) and 60 min exercise core temperature (O) and relative exercise workload (per cent VO_2 max) and 60 min exercise core temperature (△). Measurements were made on 9 male subjects who exercised for 1 h on an electrically braked cycle ergometer at 140 W (test B).

Heart rate responses
Heart rate increased rapidly with the onset of exercise (Figure 1), reaching values of 147±10 beats.min⁻¹ and 125±9 beats.min⁻¹ after 5 min of exercise in tests A and B respectively. During the remaining 55 min of exercise, heart rate increased slowly at approximately the same rate in each test. Values of 173±14 beats.min⁻¹ and 145±21 beats.min⁻¹ were recorded during the final minute of exercise in tests A and B respectively. There was no relationship between pre-exercise heart rate and VO_2 max in tests A (r=0.01) or B (r=0.02). However, heart rate recorded during the final minute of exercise in test B was inversely related to body weight (r=−0.78, p<0.05), body surface area (r=−0.72, p<0.05), absolute sweat loss (r=0.67, p<0.05), and VO_2 max (r=−0.71, p<0.05) and was positively related to the relative exercise intensity (r=0.68, p<0.05). Similar relationships were not found in test A (r=−0.42, r=−0.23, r=−0.02, r=0.37, r=−0.19 respectively).

Skin temperature responses
During both tests mean skin temperature did not increase until after 5 min of exercise. In test A values increased from 31.1±0.6°C to 32.5±1.0°C, recorded after 25 min of exercise (Figure 3). Throughout the remainder of test A, skin temperature was relatively stable, reaching 32.8±1°C during the final minute of exercise. In test B, skin temperature increased from 30.8±0.9°C to 32.4±1.1°C, recorded after 35 min of exercise. From this point onwards the change in skin temperature was relatively small and closely matched the pattern of change recorded in test A (Figure 3).

In both tests there was no relationship between skin temperature (the value recorded at rest prior to exercise, the change recorded during exercise and the value recorded during the final minute of exercise) and VO_2 max, absolute workload or the corresponding core temperature responses (Table 2). Perhaps surprisingly, in test B, there was no relationship between the skin temperature responses and the relative exercise intensity performed (Table 2).

Discussion
The results of the present experiment indicate that cardiovascular fitness (as indicated by VO_2 max) will play a major role in determining the thermoregulatory response of Man during exercise at a mild ambient temperature. This is contrary to the suggestion of Schwartz et al. that the thermoregulatory responses of Man are mainly a function of heat adaptation.

Sweat loss and VO_2 max
In agreement with Saltin and Hermansen, the results of test A indicate that sweat loss in Man is greatly dependent upon the absolute workload performed during exercise (r=0.82, p<0.01, Figure 1). However, it is also clear from the results of tests A and B that...
Thermoregulation during exercise: P.L. Greenhaff

Table 2. Values indicating the degree of association between mean skin temperature and VO2 max, absolute workload, core temperature and relative exercise intensity in tests A and B. Values shown represent the Pearson Correlation coefficient. At no point was statistical significance attained (n = 9).

<table>
<thead>
<tr>
<th></th>
<th>Pre-exercise</th>
<th>Mean skin temperature (°C)</th>
<th>Change during exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test A</td>
<td>Test B</td>
<td>Test A</td>
</tr>
<tr>
<td>VO2 max (ml min⁻¹ kg⁻¹)</td>
<td>-0.18</td>
<td>-0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>Absolute workload performed (W)</td>
<td>-0.01</td>
<td>-0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>Pre-exercise core temperature (°C)</td>
<td>0.50</td>
<td>0.32</td>
<td>0.38</td>
</tr>
<tr>
<td>Final minute exercise core temperature (°C)</td>
<td>0.54</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td>Change in core temperature (°C)</td>
<td>0.23</td>
<td>0.02</td>
<td>0.22</td>
</tr>
<tr>
<td>Relative workload performed (% VO2 max)</td>
<td>-</td>
<td>0.20</td>
<td>-0.26</td>
</tr>
</tbody>
</table>

Cardiovascular fitness (as indicated by VO2 max) will significantly influence the degree of sweat loss during exercise (r = 0.67, p < 0.05; r = 0.67, p < 0.05 respectively, Figure 2). The relationship between cardiovascular fitness and sweat loss in Man during exercise has been previously reported. However, it is important to note that in both exercise tests of the present experiment VO2 max only accounted for 45 per cent of the variation in sweat loss during exercise.

As a consequence, it is plausible to suggest that exercise-induced heat adaptation may have also influenced the sweating response. This is supported by the finding of Henane et al. that the sweating response of skiers during passive heating was more marked than that of swimmers, despite VO2 max being similar in both groups. The authors suggested that this finding may have resulted from skiers experiencing a greater degree of exercise-induced hyperthermia during exercise and thereby becoming better acclimatized than swimmers.

The results of the present experiment suggest that when exercise is performed at the same absolute workload sweat loss is not related to body weight (r = 0.57) or body surface area (r = 0.65). This finding indicates that the greater sweat loss observed in fitter individuals during test B was not a result of body weight influencing metabolic rate as has been suggested in the past. The strong relationship between sweat loss and body weight (r = 0.82, p < 0.01) and body surface area (r = 0.85, p < 0.01) in test A can probably be attributed to the finding that body weight and body surface area are related to exercise workload (r = 0.78, p < 0.05; r = 0.83, p < 0.01 respectively), which in turn is related to sweat loss (r = 0.82, p < 0.01).

Core temperature and VO2 max
The strong relationship between relative exercise intensity and core temperature during the final minute of exercise in tests B (r = 0.82, p < 0.01) supports the finding of Saltin and Hermansen that rectal temperature during exercise is closely related to the relative workload performed. As would therefore be expected, the results of the present experiment also suggest VO2 max will significantly influence core temperature during exercise; accounting for 74 per cent of the variability in core temperature measured during the final minute of exercise in test B (r = -0.86, p < 0.01, Figure 4).

A major proposal of Schwartz et al. was that VO2 max will have only a minor influence in determining core temperature in Man during exercise. This proposal was based upon the finding that VO2 max accounted for only 38 per cent of the variation in rectal temperature during exercise. The authors indicated that in situations where skin temperature is greater than ambient temperature, body heat loss will be partially dependent upon the surface area-to-mass ratio of each subject. They went on to suggest that because the surface area-to-mass ratio may be related to VO2 max and exercise core temperature, any relationship between VO2 max and core temperature during exercise may be purely coincidental.

However, the finding that during the present study body surface area and body weight were not related to VO2 max (r = 0.63, r = 0.60 respectively) or rectal temperature during the final minute of exercise in test B (r = 0.65, r = 0.64 respectively) is not in accordance with the above suggestion. The lack of agreement between the results of the present experiment and those of Schwartz et al. is probably related to the low exercise workload performed by subjects during the latter experiment (41 and 82W), resulting in rectal temperature rarely increasing above 38°C.

VO2 max has been suggested in the past to influence resting core temperature. Baum et al. reported lower resting core temperatures in male long distance runners. Drinkwater et al. reported a similar response in female athletes. Henane et al. showed a decrease in resting core temperature after a period of endurance training. However, Schwartz indicated that resting rectal temperature is more a function of the degree of heat adaptation than VO2 max. The finding in the present study that there was no relationship between VO2 max and resting core temperature in test A (r = -0.13) or test B (r = -0.10) perhaps supports this latter proposal.

Heart rate and VO2 max
The inverse relationship between final minute heart rate and VO2 max in test B (r = -0.71, p < 0.05) indicates that heart rate is more closely related to the relative workload performed than the absolute workload. Gisolfi was the first to propose that because training adaptations result in a reduced muscle blood flow for a given submaximal workload, trained individuals may have a larger volume of blood available to perfuse the skin and thereby dissipate more heat. The close relationship between heart rate responses and core temperature responses during exercise in test B (Figure 5) is possibly in agreement with this suggestion.
Skin temperature

The results of the present experiment do not support the proposal that mean skin temperature during exercise is related to the relative workload performed. No relationship was found between skin temperature and the relative ($r=0.26$) or absolute ($r=0.03$) workloads performed during exercise. The changes occurring in skin temperature during the first 30 min of exercise appear to match those of rectal temperature. However, after this time point the pattern of change in skin temperature is difficult to explain. Despite metabolic heat production and core temperature being higher in test A, skin temperature during the final 30 min of both tests was very similar (Figure 3). It is not known whether the high relative humidity at which both tests were performed (85 per cent) may have influenced the degree of heat loss from the skin surface. However, it is plausible to suggest that the close similarity in skin temperatures during the second half of both tests may have arisen because sweat was unable to evaporate from the skin surface.

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References